

# Direct-Digital-Drive Microring Modulator

Yossef Ehrlichman, *Member, IEEE*, Ofer Amrani, *Member, IEEE* Shlomo Ruschin, *Member, OSA*

**Abstract**—The method of Direct Digital Drive is applied to a microring resonator. The microring resonator is thus controlled by a segmented set of electrodes each of which is driven by binary (digital) signal. Digital linearization is performed with the aid of digital memory lookup table. The method is applied to a single microring modulator to provide an M-bit digital-to-analog converter (DAC), which may also be viewed as an M-level pulse amplitude modulator (M-PAM). It is shown, by means of simulation, that a 4-bit DAC can achieve an effective number of bits (ENOB) of 3.74bits. Applying the same method for two rings, enables the generation of two-dimensional optical M-QAM signals. It is shown, by means of simulation, that a 16-QAM modulator achieves an EVM better than -30dB.

**Index Terms**—Microring modulators, optical digital-to-analog converter, optical M-PAM, optical M-QAM.

## I. INTRODUCTION

ATTEMPTING to apply photonic technologies to data processing has been taking place for several decades. Yet, their implementation in practical systems remained limited and failed to penetrate practical processors. Many demonstrated optical devices are still oversized, were based on exotic materials and needed rather complicated interfacing with other electronic components. This paper takes advantage of recent developments in Silicon microphotronics and novel interfacing schemes in order to realize photonic components for fast communication and signal processing. In addition to its practical potential, as presented, the ideas exposed herein present basic physical and mathematical challenges. Microring modulators were proposed and demonstrated for analog signal modulation and for simple digital modulation, such as On-Off-Keying (OOK). Recently, microring modulators were investigated for advanced digital modulation formats such as PAM [1] [2] [3], QPSK [4] and even QAM [5] [6]. All the works mentioned above ([6] excluded) use an analog voltage signal to drive the modulator. The application of analog signals usually calls for mediating electronic circuitry, such as digital-to-analog conversion. In the current work we promote the application of the, so-called, *Direct Digital Drive* (DDD) [7] method for use with microring resonators. DDD allows the utilization of only two voltage levels directly on the photonic device; it makes the need for mediating devices, such as electrical digital-to-analog converter, unnecessary.

In the first part of this work we present a design of an N-bit digital-to-analog converter. A digital-to-analog converter is a device that converts an N-bit digital word to a corresponding analog (voltage) representation. A 4-bit DAC produces 16, equally spaced analog levels and can therefore be viewed as (a digitally controlled) 16-PAM modulator. In the second part of this work we extended a previous work [5] for generating M-QAM signals with microring modulators by utilizing the DDD

approach. An all-digital M-QAM modulator is thus presented.

## II. MULTI-ELECTRODE MICRORING DIGITAL-TO-ANALOG CONVERTER/M-PAM MODULATOR

As an example, consider the 4-bit optical DAC based on a microring modulator, illustrated in Figure 1. The device basic layout is similar to previously published microring resonators. A CW light of wavelength  $\lambda$  and intensity  $I_{in}$  is coupled from the waveguide to the microring. The coupling coefficient between the waveguide and the microring is denoted by  $t$  and the loss per round trip inside the microring is  $a$ . The light inside the microring is modulated by several, in this example  $M = 5$ , independent phase shifter segments (electrodes). The phase shifter can be implemented as reversed-bias pn-diode or as zig-zag pn diode, etc. Hereinafter, each phase shifter will be referred to as an *electrode*.

At its electrical input, the device accepts an  $N = 4$  bits digital word, denoted  $D_i$ , where  $i = \{1 \dots 2^N\}$ . The input word is mapped onto each of the 5 electrodes via the digital-to-digital converter (DDC). In essence, the DDC converts a 4-bit input to a 5-bit output, which, in turn, control the 5 electrodes. Note that each electrode is driven by one of two voltage levels, 0 and  $V_1$ , representing binary 0 and 1. Described as such, the DDC is basically a lookup-table that can be realized by a (high speed) digital memory.

An optical modulator is typically characterized by the product  $V_\pi \cdot L$  where  $V_\pi$  is the voltage whose application to an electrode of length  $L$ , induces a phase shift of  $\pi$ . Without loss of generality, we set  $L = 2\pi R_1$ , i.e. as the circumference of the microring, where  $R_1$  is the radius of the ring. Let  $j$ , denote the index of the electrodes (in this example  $j = 1 \dots 5$ ). Assume that the length of each electrode is given by:  $L_j = L \cdot 2^{-j}$ . Note that  $L > \sum L_j$ .

If a voltage  $V_1$  is applied to electrode  $j$ , the induced phase shift  $\phi_j$  will be:

$$\phi_j = k \frac{2\pi}{\lambda} \Delta n b_j L_j, \quad (1)$$

where  $\Delta n$  is the effective refractive index modulation due to the applied voltage  $V_1$  on phase shifter  $j$ ,  $k$  is an empirical constant that accounts for both the optical confinement and the coefficient of the charge density induced refractive index change. The parameter  $b_j$  is a binary quantity that indicates whether voltage  $V_1$  was applied to phase shifter  $j$ . The dependance between  $\Delta n$  and the applied voltage  $V_1$  is known to be a nonlinear function,  $f(V_1)$ . The exact relation depends on the phase shifter design. The intensity transmission of the DDD multi-electrode microring structure can be written as:

$$I_{out} = I_{in} \frac{a^2 - 2ta \cdot \cos \left( \sum_{j=1}^M b_{ij} L_j \right) + t_1^2}{1 - 2ta \cdot \cos \left( \sum_{j=1}^M b_{ij} L_j \right) + t^2 a^2}, \quad (2)$$

where a binary matrix  $B_i = \{b_{ij}\}$  of dimensions  $M \times N$  holds the mapping of the  $N = 4$ -bit input word  $D_i$  on the  $M = 5$  electrodes - evidently, a highly non-linear transmission.

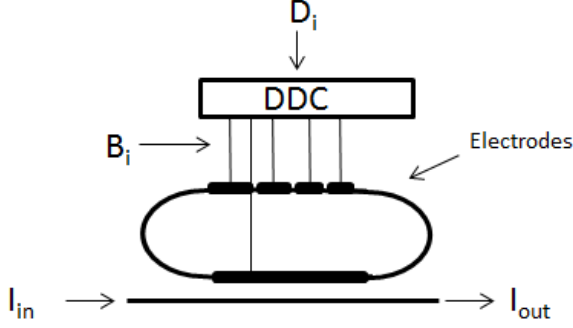


Fig. 1. Schematic illustration of a multi-electrode microring DA.

#### A. M-PAM: the design process

To maximize the output dynamic range (DR), the microring resonator should be in critical coupling,  $a = t$ . This will allow the smallest possible output intensity level to approach 0.

Figure 2 shows the output intensity of a microring resonator for phase shifts between 0 and  $\pi$ . Phase shifts greater than about  $0.5[\text{rad}]$  contribute very little to the output dynamic range because of the high nonlinearity of the microring modulator. Hence, the voltage  $V_1$  will be set so as to produce the intensity  $I_{\phi_1} = I_{in} - \Delta I$ . The quantity  $\Delta I$  is chosen as a tradeoff between (best achievable) linearity and output dynamic range. Smaller values of  $\Delta I$  can increase the output dynamic range, but also will reduce the linearity of the device, unless additional electrodes are added. A dynamic range of about 90% of the total available DR will keep the electrode count low and close to the input bit length. In this example  $V_1$  was set to induce a phase shift that leads to an output dynamic range of about 93%.

Figure 3 shows the output intensity of a 4-bit DAC (16 levels on a straight line), based on a microring modulator with 5 electrodes. Figure 4 shows a sinewave generated with the proposed device. The linearity of the DAC can be quantified by standard figure of merits: its Differential Non-Linearity (DNL) is 0.2 bits; the Integral Non-Linearity (INL) is 0.4bits and the Effective Number of Bits (ENOB) is 3.74bits.

### III. MULTI-ELECTRODE MICRORING M-QAM MODULATOR

In the previous sections we presented the design of a DAC, which is equivalent to a PAM modulator, by using a single microring modulator with several electrodes driven by a digital signal. In this section we use a two microring configuration to generate M-QAM (two-dimensional) signal constellations. Quadrature amplitude modulation (QAM) is a modulation scheme that conveys data by means of modulating both the amplitude and the phase of a sinusoid carrier thus providing spectral efficiencies in excess of 2bit/symbol. In previous work [5], we introduced a method for generating

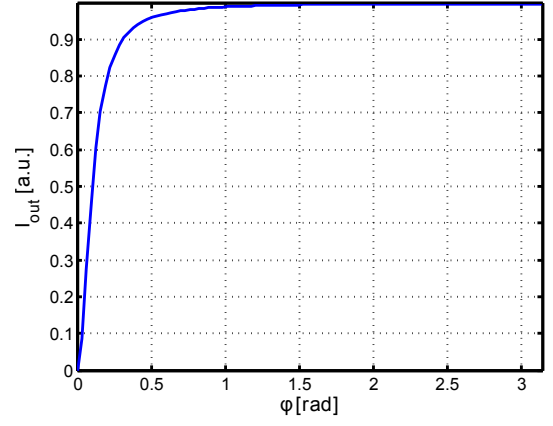


Fig. 2. The output intensity of a microring resonator for phase shifts between 0 and  $\pi$ .

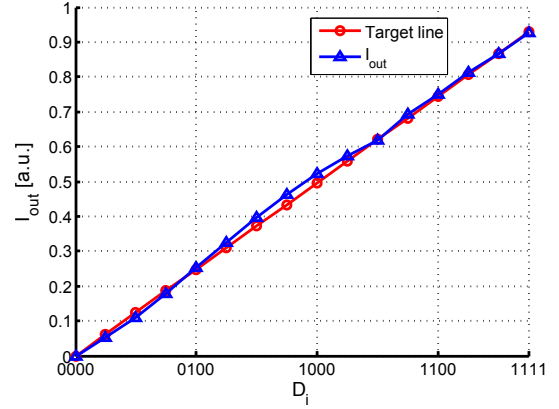


Fig. 3. The output intensity of an ideal output of a 4-bit DAC (16 levels on a straight line) compared to a DDD microring modulator with 5 electrodes.

optical M-QAM signals by using two mutually decoupled microring modulators. In this configuration, one ring was used to generate the amplitude of the desired signal (perturbed by some deterministic phase shift), while the second ring was used to complement the phase required to obtain the desired complex signal. The electronic input to this modulator was an analog voltage.

Herein, in order to drive the two rings with digital (two-level) signals, we split the electrode into segments. An M-QAM modulator is schematically depicted in Figure 5.

#### A. M-QAM: the design process

The design process is similar to the one described in Section II-A except that we now have to generate complex signals rather than intensity levels only. The role of the modulator is to generate a specific constellation of points consisting of  $M$  distinct complex points (also referred to as *signals*); the constellation points can be generally formulated as follows:

$$s_i = r_i e^{j\theta_i}, \quad r_i > 0, \quad 0 \leq \theta_i \leq 2\pi, \quad i = 1, \dots, 2^M. \quad (3)$$

The proposed modulator is described by means of an example. Figure 5 depicts a 16QAM optical modulator based on two micro-ring resonators equipped with multiple electrodes. The electrodes in this example are divided between the two micro-rings: 7 electrodes on each micro-ring.

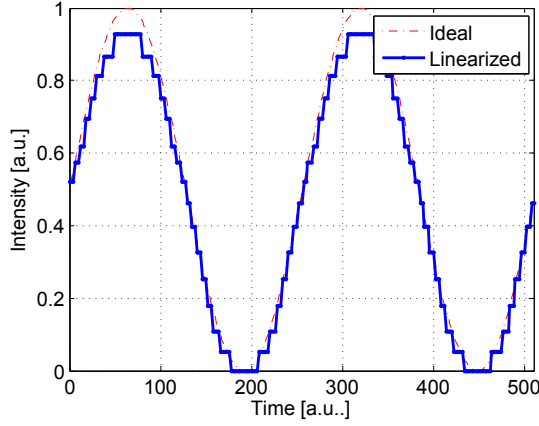


Fig. 4. A sinewave generated by the 4-bit DAC of Fig. 1

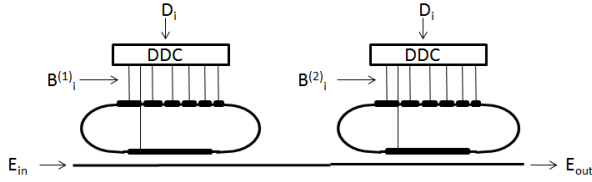


Fig. 5. 16QAM Modulator based on two, multi-electrode, DDD micro-ring resonators. A 4-bit digital input,  $D_i$ , is mapped by the DDC to a 14-bit output that drives the 14 segmented electrodes. The electrode lengths (per micro-ring) follow a divide-by-two sequence. The DDC, shown here for exposition purposes as two separate boxes, is actually a single memory device.

As input, this QAM modulator accepts a 4-bit digital word, denoted  $D_i$ . The 4-bit input word is mapped onto each of the 14 electrodes via the DDC. Thus, each electrode is driven by one of two voltage levels, 0 or  $v$ , representing binary 0 and 1, respectively.

More generally, Let  $\mathbf{L}^{(1)} = (L_1^{(1)}, L_2^{(1)}, \dots, L_{N_1}^{(1)})$  and  $\mathbf{L}^{(2)} = (L_1^{(2)}, L_2^{(2)}, \dots, L_{N_2}^{(2)})$  be two vectors of dimensions  $N_1$  and  $N_2$ , whose elements correspond to the lengths of the electrodes of the first microring and the second microring, respectively. Let  $\mathbf{B}^{(1)}$  be a binary  $M \times N_1$  matrix. Row  $i$  of  $\mathbf{B}^{(1)}$ ,  $B_i^{(1)}$ , holds the mapping from input  $D_i$  onto the  $N_1$  electrodes of the left ring. Likewise, binary matrix  $\mathbf{B}^{(2)}$ , of dimensions  $M \times N_2$ , holds the mappings from each of the input digital words to the  $N_2$  electrodes of the right ring. With this nomenclature, the output of the modulator can be formulated as a function of the digital input  $D_i$ :

$$E_{out}(D_i) = E_{in} \exp[j(\pi + \phi_1)] \frac{\alpha_1 - t_1 \exp(-j\phi_1)}{1 - t_1 \alpha_1 \exp(j\phi_1)} \cdot \exp[j(\pi + \phi_2)] \frac{\alpha_2 - t_2 \exp(-j\phi_2)}{1 - t_2 \alpha_2 \exp(j\phi_2)} \quad (4)$$

and the phase shift are

$$\phi_1 = \pi \frac{v}{v_\pi} \sum_{j=1}^{N_1} B_{ij}^{(1)} L_j^{(1)} \quad (5)$$

$$\phi_2 = \pi \frac{v}{v_\pi} \sum_{j=1}^{N_2} B_{ij}^{(2)} L_j^{(2)} \quad (6)$$

where  $E_{in}$  denotes the amplitude of the optical field entering the modulator.

The geometrical structure and the loss and coupling parameters are set in a similar manner to the description in [5]. The first ring is designed to work in critical coupling for which  $t = a$  in order to generate the largest span of amplitudes. The second microring is designed to work in under-coupling regime,  $t < a$ , to act as a phase shifter with minimum amplitude loss. By applying all possible combinations of the digital words  $B_i$ , a finite pool of points, of maximum cardinality  $2^{N_1+N_2}$ , can be generated.

As an example, a pool of (green) points is shown in Figure 6 for  $N_1 = N_2 = 7$ . From this large pool of possible points, one can choose a finite set of points that form a constellation for digital optical communications, 16-QAM in this example. An ideal set of points that constitute a 16-QAM constellation, as suggested by Eq. 3 with  $M = 4$ , is portrayed by the red triangles in Figure 6. Out of the green pool of  $2^{7+7}$  signal points, we first select the 16 signals that provide the best match for the ideal 16 points. The selected set of best points amounts to a mapping between 16  $D_i$  digital input values and the corresponding  $B_i$ 's, and is executed by the DDC.

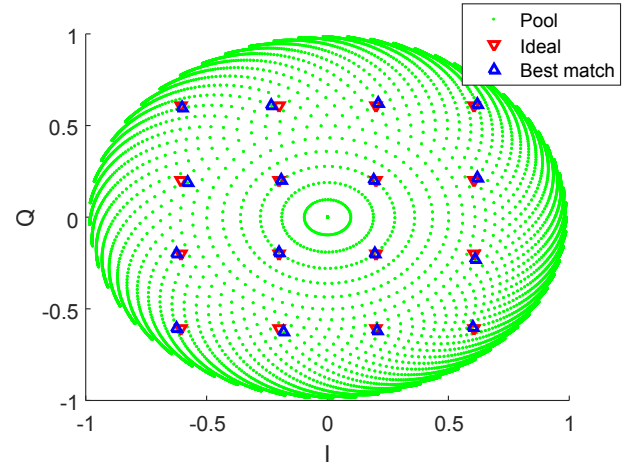


Fig. 6. 16QAM with  $N_1 = N_2 = 7$ . The EVM obtained is  $-30.6dB$ .

As can be seen in the figure, the selected points are not identical to the ideal points, thus producing an error. To quantify this error, we employ the Error Vector Magnitude (EVM) [5] measure. For the above example the EVM is  $-30.6dB$ . Note that the EVM can be further reduced by increasing the number of electrodes in each microring. Such an increase will allow generating a denser pool of points from which one can select a desired set of constellation points with higher accuracy. Table I presents the obtained EVM for various constellations and varying number of electrodes. It shows the EVM for 16-QAM with  $6 + 6$  and  $7 + 7$  electrodes. The difference between these configurations is 9dB. It can be seen that the inherent nonlinearity of the microring leads to a more involved implementation of M-QAM modulators compared to M-PAM modulators. The table also presents results for 64-QAM and 256QAM. While for 64QAM we achieve EVM better than  $-30dB$  with  $7+7$  electrode configuration, 256QAM requires one additional electrode in the amplitude-related modulator ring to

TABLE I  
EVM AS A FUNCTION OF NUMBER OF ELECTRODE

$M$ -QAM	$N_1$	$N_2$	EVM [dB]
16	6	6	-21.8
16	7	7	-30.6
64	7	7	-30.4
256	7	7	-26.9
256	8	7	-30.9

achieve such EVM.

### B. Higher order QAM constellations

The number of distinct electrode segments that can be effectively mounted on a single microring is obviously limited. This, however, does not limit the proposed technology, as the original configuration can be augmented by additional rings with additional electrodes. Thus for example, rather than generating 256-QAM with 7 and 8 electrodes on each ring, one can utilize 4 rings with 5 electrodes on each ring: two of the rings will act as amplitude modulators while the other two will act as phase modulators, as depicted in Figure 7. For the same parameters as above, with the new configuration of 4 microrings, EVM of  $-33dB$  is achieved.

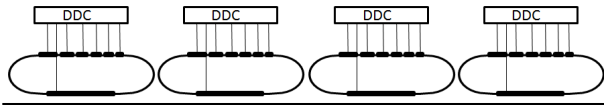


Fig. 7. Multi micron configuration. The number of microring has been increased, but the number of electrodes per microring was reduced.

## IV. PRACTICAL IMPLEMENTATION

The practical implementation of the DDD modulators is not obvious. Next, we briefly discuss issues that are associated with the implementation of the above devices in silicon photonic technology. Silicon has the potential of full integration of optics and electronics either in a monolithic or a hybrid process. The first problem that arises with silicon is that the plasma dispersion effect (which is used widely to make phase shifters for silicon modulators) induces a voltage dependent loss. Meaning, it is impossible to make a lossless phase shifter. However, this problem can be alleviated by the DDD approach. More specifically, the problem is that the VDL (Voltage Dependent Loss) will reduce the average optical power and hence "compress" the signal pool. The solution is simply to configure the DDC to map (shrink) the required constellation to a lower average optical power.

The second problem that might arise is that in order to generate a phase shifter to induce phases between 0 and  $2\pi$ , a large voltage signal will be needed. This problem can be solved by using the multiple microring configuration as discussed in the previous section. For example, instead of using a single ring to induce the  $2\pi$  phase shift, we can use multiple modulators to induce the phase we are targeting.

## V. CONCLUSION

We presented application of the Direct Digital Drive approach to microring resonators. We showed that this approach enables one to realize a digitally driven optical devices, that include compact M-PAM modulator and DACs. Extending the approach to more then one microring, enables the generation of optical M-QAM constellations. We showed that it is possible to generate any constellation order either by using a large number of electrodes, or by using a small number of electrodes but employ additional microring modulators.

## REFERENCES

- [1] M. S. Hai, M. M. P. Fard, and O. Liboiron-Ladouceur, "A low-voltage pam-4 soi ring-based modulator," in *Photonics Conference (IPC), 2014 IEEE*. IEEE, 2014, pp. 194–195.
- [2] J. Ding, F. Zhang, W. Zhu, P. Zhou, Q. Chen, L. Zhang, and L. Yang, "Optical digital to analog converter based on microring swithes," 2014.
- [3] S. Karimelahi and A. Sheikholeslami, "Pam-n signaling by coupling modulation in a ring resonator," *Optics Letters*, vol. 40, no. 3, pp. 332–335, 2015.
- [4] P. Dong, C. Xie, L. L. Buhl, and Y.-K. Chen, "Silicon microring modulators for advanced modulation formats," in *Optical Fiber Communication Conference*. Optical Society of America, 2013, pp. OW4J–2.
- [5] Y. Ehrlichman, O. Amrani, and S. Ruschin, "Generating arbitrary optical signal constellations using microring resonators," *Optics express*, vol. 21, no. 3, pp. 3793–3799, 2013.
- [6] S. Karimelahi and A. Sheikholeslami, "Quadrature amplitude modulation (qam) using binary-driven coupling-modulated rings," *Optics Communications*, 2016.
- [7] Y. Ehrlichman, O. Amrani, and S. Ruschin, "Improved digital-to-analog conversion using multi-electrode mach zehnder interferometer," *J. Lightw. Technol.*, vol. 26, no. 21, pp. 3567–3575, Nov.1, 2008.